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ELECTRICAL PERFORMANCE OF
THREE SOLAR THERMOELECTRIC
TEST SECTIONS

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16. Abstract <p>Current-voltage characteristics were measured for three planar test sections of a solar thermoelectric generator designed to operate at 0.25 AU from the sun. Each test section consisted of nine silicon-germanium thermocouples mechanically attached to a beryllium radiator plate. Measurements were made at average hot junction temperatures in the range of 640° to 940° C. All three test sections produced the design power output of 2.8 watts at 1.0 volt; however, junction temperatures approximately 50° C higher than predicted were required to achieve this power because of poor thermal contact between the thermocouple stud and the radiator plate. One of the tests sections, life-tested for 3000 hours, exhibited an increase in internal resistance of about 14 percent, corresponding to a decrease in power output of about 6 percent.</p>					
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ELECTRICAL PERFORMANCE OF THREE SOLAR

THERMOELECTRIC TEST SECTIONS

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SUMMARY

Three test sections of a solar thermoelectric generator, designed for minimum specific weight at 0.25 AU from the sun, were electrically tested. Each test section consisted of nine silicon-germanium thermocouples mechanically attached to a beryllium radiator plate. Measurements were made at average hot junction temperatures in the range of 640° to 940° C.

The electrical characteristics of the three test sections were essentially identical, each producing a design power output of 2.8 watts at 1.0 volt. However, hot and cold junction temperatures approximately 50° C higher than predicted were required to achieve this power because of poor thermal contact between the thermocouple stud and the radiator plate. One test section, life-tested for 3000 hours, exhibited an increase in internal resistance of 14 percent, corresponding to a decrease in power output of about 6 percent.

INTRODUCTION

For solar probe applications, a study (ref. 1) has shown that silicon solar cells could provide nearly constant electrical power from 1 AU to on the order of 0.25 AU (an astronomical unit, AU, is defined as the mean-earth-sun distance). However, for closer distances, thermal control problems are anticipated which may require the use of an alternate power system such as a solar thermoelectric (TE) flat-plate generator. The thermoelectric generator would have a much higher temperature capability than solar cells; could be designed to operate normal to the sun's ray at 0.25 AU; and, with tilting used to provide thermal flux control, would provide constant power to distances of 0.1 AU or less. Hence, for continuous electrical power generation from earth to a

near-sun design point, a hybrid system could be used, that is, solar cells between Earth and the distance from the sun where solar-cell temperature limits are reached and a solar TE flat-plate generator for closer distances.

Under contract NAS 3-10600, the RCA Corporation, Harrison, New Jersey, designed a 150-watt solar flat-plate thermoelectric generator for minimum specific weight, based on a design point of 0.25 AU (ref. 2). In order to demonstrate the feasibility of the concept, three test sections of the generator were fabricated (ref. 3), instrumented, and delivered to Lewis for testing. The pertinent results of the generator design study are presented here for completeness.

Number of thermocouples	480
Current, A	5.63
Voltage, V	26.6
Power, W	150
Efficiency, percent	3.57
Weight, kg (lb)	6 (13.2)
Area, m ² (ft ²)	0.383 (4.12)
Specific weight, kg/m ² (lb/ft ²)	15.8 (3.23)
Power/area, W/m ² (W/ft ²)	382 (36.4)
Power/weight, W/kg (W/lb)	24.8 (11.3)
Hot junction temperature, °C (°F)	790 (1454)
Cold junction temperature, °C (°F)	430 (806)
Design-point distance, AU	0.25

The current-voltage characteristics of the three test sections were measured and one test section was life-tested for 3000 hours. In addition, a nine-thermocouple prototype test section was life-tested for 5500 hours in a separate experiment. The tests were conducted to provide a first-order evaluation of the mechanical and electrical behavior of the test sections and to uncover areas in which further development might be required. The results of these tests are reported herein.

DESCRIPTION

Test Section

Each of the planar test sections consists of nine silicon-germanium (Si-Ge) thermocouples arranged in a 3-by-3 array and electrically connected in series. A test section is shown in figure 1 and a sketch of a Si-Ge thermocouple is shown in figure 2. The overall dimensions of the test section are 8.9 by 8.9 by 2.5 centimeter. Each individual Si-Ge thermocouple consists of a phosphorus-doped (n-type) and a boron-doped (p-type)

thermoelement metallurgically bonded to a heat receptor plate or "hot shoe." The Si-Ge alloy used is nominally 63.5-atomic-percent silicon while an 85-weight-percent silicon - 15-weight-percent molybdenum alloy is used for the hot shoe. The thermoelements are bonded through a cold stack to a beryllium mounting stud at the cold end. The cold stack consists of a tungsten shoe, a copper pedestal, a tungsten compensator, and a copper strap used as an electrical lead for each thermoelement. An alumina disk is included between the cold stack and the mounting stud to electrically isolate the thermocouple from the beryllium radiator plate. The thermocouples are mechanically fastened to the radiator plate, and the outer radiator plate surface is coated with calcium titanate to provide a high-emittance surface. Fibrous insulation (Johns-Manville Min-K 2002) is used between the thermocouples to minimize shunt heat loss. The insulation is machined in bulk and fitted into large areas. Small, irregular areas are filled with loose microquartz insulation.

It is important to note that although a selective solar absorptance coating was assumed in designing the generator, no such coating was provided on the hot shoes of the test sections. Hence, no attempt was made to duplicate the solar spectrum at 0.25 AU in heating the test sections.

Instrumentation

On each test section, five of the nine Si-Ge thermocouples were instrumented with Chromel-Alumel thermocouples at the cold end and tungsten - 3-percent-rhenium/tungsten - 25-percent-rhenium thermocouples on the hot shoes. The five Si-Ge thermocouples instrumented were located at the four corners and the center of the array. In addition, 10 Alumel voltage probes were provided (located on the copper connecting straps). Two copper straps were used, one at each end of the circuit, as power taps.

Test Fixture

The test fixture, shown in figure 3, consists of two infrared strip heaters, arranged so as to uniformly heat a 8.9- by 8.9-centimeter test area. Since each infrared lamp has an active length of 15 centimeters, two water-cooled copper masks were required, one at each end, to give the desired 8.9-centimeter dimension. For the initial performance mapping of the test sections, the fixture was fastened to the hemispherical end cap of a vacuum chamber having a liquid-nitrogen-cooled, blackened shroud. (The test section was supported in the test fixture by four spring-loaded pins mounted in an aluminum frame. The pins made point contact with the radiator plate edges.) A brass plate bolted to the chamber bulkhead was used for all electrical and coolant feedthroughs.

In the subsequent life-testing of one test section, a different vacuum system was used. In this system, the radiator viewed a conventional glass bell jar instead of the blackened shroud used in the performance tests. The effect on the operating temperatures of the test section was negligible.

TESTING PROCEDURE

Performance Mapping

Each test section was tested in the following manner: Room-temperature resistance of the entire nine-thermocouple string was measured both before and after installation in the vacuum chamber.

The test section was then connected in the load circuit, as shown schematically in figure 4. Two potentiometers, 0 to 2 ohms and 0 to 8 ohms, connected in parallel, were used as the variable resistance load and a 50-milliohm shunt was used to measure thermoelectric current.

After a vacuum pressure of 10^{-5} torr or less was reached, the heater power was turned on and was gradually increased to achieve operating conditions. Typically a heating rate of 25°C per minute was used. Because of uncertainties regarding the hot shoe temperature-sensing thermocouples (e.g., location, accuracy, behavior in test environment, and intimacy of contact with device), it was decided to use the output of the test section itself to define reference operating conditions. Hence, the test section was heated to temperatures which resulted in the predicted output voltage of 1 volt and current of 2.8 amperes with a load-to-internal-resistance ratio of about 1.2. Typically, an average hot junction temperature of about 840°C was required to achieve the reference design power. This is discussed in more detail later in the report. With the heater input power fixed, the current-voltage (I-V) characteristics were determined by varying the external load and allowing the test section to reach a steady-state condition (usually within 15 min) before recording the I-V point. Three such current-voltage points, in addition to an open-circuit voltage point, were recorded. The procedure was then repeated for average hot junction temperatures of 640° , 740° , and 940°C . These data are tabulated in appendix A. The resulting I-V characteristics of the three test sections are presented in figure 5.

Initially, the W-3Re/W-25Re thermocouples provided on five of the nine hot shoes by the vendor were used to determine the hot junction temperature. However, it was immediately obvious that the W-3Re/W-25Re thermocouple readings were not representative of true junction temperatures since the corresponding open-circuit voltages were higher than predicted for Si-Ge. As a result it was decided to use the output of the Si-Ge thermocouple itself as an indication of the hot junction temperature. A typical

hot side temperature distribution is shown in figure 6, where junction temperatures obtained from the Si-Ge output are compared to those indicated by the W-3Re/W-25Re thermocouples.

Life-Test Procedures

Test section 3 was arbitrarily selected for life testing. Again, the internal resistance was measured and the test section was heated to nominal reference design conditions. The test section was operated for 3000 hours. The data system was programmed to automatically record the load current and various temperatures and voltages every 12 hours. Internal resistance was measured periodically using the method outlined in appendix B.

There were six shutdowns during the 3000-hour test, caused by various system malfunctions. There were no indications that any of the shutdowns were due to the module itself. Also, there were three controlled shutdowns very early in the life-test to allow modification of auxiliary equipment.

TEST RESULTS

Performance Mapping

The resistance of the three test sections, as received, was found to be consistent with values quoted by the vendor, being 132, 124, and 119 milliohms at room temperature for test sections 1, 2, and 3, respectively. The resistance of the individual thermocouples, including representative bond-contact resistance, is presented in reference 3.

Comparison of the I-V characteristics of test sections 1, 2, and 3 (figs. 5(a), (b), and (c), respectively) indicates that the performance of all three sections is nearly identical. Based on the thermoelectric panel design analysis (ref. 2), the nine-thermocouple test sections are to produce 2.8 watts at 1 volt at a hot junction temperature of 791°C and a cold junction temperature of 430°C , resulting in a temperature difference across the element of 361°C . The temperatures actually required to achieve 2.8 watts at 1 volt are tabulated for each of the three test sections and compared to the reference design temperatures in table I. Note that while the measured output of 2.82 ± 0.07 watts at 1.0 ± 0.01 volts was obtained with a temperature difference of $361^{\circ} \pm 5^{\circ}\text{C}$, corresponding to the reference design, resultant hot and cold junction temperatures exceeded reference design temperatures by about 50°C . This is due primarily to poor thermal contact between the thermocouple stud and the radiator baseplate.

For test section 1, this poor thermal contact resulted in a measured cold-stack temperature difference ΔT_{CS} (between the cold junction and radiator surface) of 43°C compared to a calculated value of 15°C . Although no instrumentation was provided on the radiator surface of test sections 2 and 3, it is reasonable to assume a similar cold-stack ΔT existed for these test sections.

Techniques to improve the thermal contact between the stud and radiator, and thereby reduce ΔT_{CS} , have since been developed under another program (ref. 4). It has been established that a ΔT_{CS} of 15°C can be achieved by using a modified stud design which permits application of 10 to 15 inch-pounds (113 to 170 cm-N) of torque in tightening the mount nut to the stud. For the solar test sections the applied torque was limited to about 1 inch-pound (11.3 cm-N) since greater torques were found to cause breakage of the stud at the neck of the tapered region.

Another factor which might cause the measured junction temperatures to deviate from design values is the uncertainty regarding the emittance of the calcium titanate coating. It was found that an initial "heat treatment" of the coated radiator was required each time the test section was exposed to the atmosphere to stabilize the emittance of the surface (typically about 3 hr of operation at a radiator surface temperature of about 500°C). During this time, the radiator surface temperature was observed to decrease gradually for a fixed input power indicating a gradual increase in emittance of the calcium titanite. Since no direct emittance measurements were made, the "stabilized" value of emittance can only be assumed. If, for example, this value were 0.75 rather than the 0.85 used in the reference design analysis, the radiator temperature would increase by about 25°C . This, in addition to the cold-stack temperature drop, would account for the 50°C variation from design values in junction temperatures. Additional uncertainties regarding the thermal conductivity of the Johns-Manville Min-K 2002 thermal insulation and the importance of edge effects in testing small panels cannot be readily estimated; however, it appears that they are relatively minor.

Life-Test Results

As is generally known, Si-Ge thermocouples exhibit some degradation during the first 1500 hours of operation, the amount being dependent for the most part on the temperature range over which the thermoelements operate (ref. 5). Typically, this initial degradation is of the order of 5 percent. Following this 1500-hour "burn-in," the material is considered to be essentially stable, undergoing an additional 5 to 7 percent degradation during the next 20 000 to 30 000 hours of operation. Since solar panel test section 3 was subjected to several hundred hours of performance mapping prior to placing it on life-test, it was obvious that the degradation rates described above would not be observed. (Since the degradation mechanisms are time- and temperature-dependent

and are reversible, life-testing of an as-fabricated Si-Ge device would be required to observe the true degradation rates.)

Another complication was the behavior of the calcium titanate emittance coating on the radiator plate. As previously explained, the coating required a "heat treatment" each time it was exposed to atmosphere in order to obtain the desired emittance. Thus, after test section 3 was installed in the life-test fixture and heated to reference design power output, the cold junction temperatures were higher than anticipated. As shown in figure 7, this decrease in cold junction temperature due to the improving emittance occurred during the first 100 hours of operation. A corresponding variation in output power during this period is also shown in the same figure.

Because of the difficulties encountered in establishing life-test conditions, a number of adjustments in input power were made during the first 300 to 400 hours. However, as shown in figure 7, the performance of the test section was essentially stable from 400 to 3000 hours, during which time the input power was held constant and the output voltage of the test section was maintained at 1 volt. Actually, under the circumstances, the internal electrical resistance, presented as a function of time in figure 7, is more useful in characterizing the performance of the solar panel test section. Note, for example, that during the first 600 hours the internal resistance increased from 0.315 to 0.340 ohm, while during the remaining 2800 hours it increased from 0.340 to 0.360 ohm. This is in accordance with the predicted behavior of Si-Ge thermocouples (ref. 5), the increase in resistance being attributed to the precipitation of phosphorus dopant and subsequent diffusion to nucleation sites with an attendant loss of current carriers.

In a separate experiment, a nine-thermocouple prototype test section was life-tested for 5500 hours. A power degradation of about 8 percent was observed after 5500 hours operation with an attendant resistance increase of 18 percent. The details of this test are given in appendix B.

SUMMARY OF RESULTS

Performance testing of three uncoated solar thermoelectric test sections produced the following results:

1. The reference design output power of the test sections, 2.8 watts at 1 volt, was achieved at the design temperature difference of $361 \pm 5^{\circ}\text{C}$; however, hot and cold junction temperatures approximately 50°C higher than predicted were required primarily because of poor thermal contact between the thermocouple stud and the radiator plate.

2. The electrical performance characteristics of the three test sections, as received, were essentially identical.

3. One test section, life-tested for 3000 hours at reference design conditions, exhibited an increase in internal electrical resistance of about 14 percent. Comparison of

life-test data from a similar module (see appendix B) indicates that a resistance increase of 14 percent is accompanied by a power decrease of about 6 percent.

4. Except for a selective solar absorber coating, the feasibility of the weight-optimized design of the solar thermoelectric converter has been demonstrated.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 9, 1970,
120-27.

APPENDIX A

TABULATION OF DATA

Test Section 1

Parameter	Hot shoe number										Average
	32	52	17	45	31	48	38	46	49		
Run 21-1; current, 0; total voltage, 2.219 V; total power, 0											
Hot junction temperature (calc), T_{HJ} , °C	938.5	-----	936	-----	941	-----	944	-----	950.5	942	
Cold junction temperature (meas), T_{CJ} , °C	483.5	-----	513	-----	492	-----	517	-----	508.5	503	
Temperature difference, ΔT , °C	455	-----	423	-----	449	-----	427	-----	442	439	
Radiator temperature (meas), T_R , °C	443	-----	474	-----	432	-----	467	-----	443	452	
Voltage, V	0.2542	0.2437	0.2367	0.2553	0.2517	0.2538	0.2392	0.2190	0.2477	---	
Run 21-2; current, 2.01 A; total voltage, 1.492 V; total power, 3.0 W											
Hot junction temperature (calc), T_{HJ} , °C	928	-----	934	-----	934	-----	939	-----	941	935	
Cold junction temperature (meas), T_{CJ} , °C	495	-----	527.5	-----	505	-----	528.5	-----	521.5	515	
Temperature difference, ΔT , °C	433	-----	406.5	-----	429	-----	410.5	-----	419.5	420	
Radiator temperature (meas), T_R , °C	452	-----	486	-----	443	-----	478	-----	454	463	
Voltage, V	0.1773	0.1605	0.1564	0.1739	0.1743	0.1728	0.1595	0.1355	0.1661	---	
Run 21-3; current, 3.32 A; total voltage, 1.001 V; total power, 3.32 W											
Hot junction temperature (calc), T_{HJ} , °C	930	-----	922	-----	934	-----	928	-----	933	929	
Cold junction temperature (meas), T_{CJ} , °C	505	-----	538	-----	514	-----	538	-----	532	525	
Temperature difference, ΔT , °C	425	-----	384	-----	420	-----	390	-----	401	404	
Radiator temperature (meas), T_R , °C	460	-----	494	-----	451	-----	488	-----	461	471	
Voltage, V	0.1249	0.1041	0.1021	0.1192	0.1221	0.1180	0.1054	0.0790	0.1110	---	
Run 21-4; current, 4.61 A; total voltage, 0.5029 V; total power, 2.31 W											
Hot junction temperature (calc), T_{HJ} , °C	945	-----	898	-----	946	-----	912	-----	921	924	
Cold junction temperature (meas), T_{CJ} , °C	512.5	-----	546	-----	523	-----	544	-----	540	533	
Temperature difference, ΔT , °C	432.5	-----	352	-----	423	-----	368	-----	381	491	
Radiator temperature (meas), T_R , °C	467	-----	503	-----	459	-----	494	-----	470	478	
Voltage, V	0.0720	0.0467	0.0476	0.0632	0.0686	0.0616	0.0520	0.0230	0.0557	---	
Run 21-5; current, 0; total voltage, 1.976 V; total power, 0											
Hot junction temperature (calc), T_{HJ} , °C	841	-----	840	-----	853	-----	848	-----	855	847	
Cold junction temperature (meas), T_{CJ} , °C	444	-----	470	-----	458	-----	471	-----	465	462	
Temperature difference, ΔT , °C	397	-----	370	-----	395	-----	377	-----	390	385	
Radiator temperature (meas), T_R , °C	411	-----	440	-----	407	-----	432	-----	416	421	
Voltage, V	0.2249	0.2166	0.2095	0.2265	0.2232	0.2238	0.2136	0.1984	0.2210	---	
Run 21-6; current, 1.332 A; total voltage, 1.503 V; total power, 2.05 W											
Hot junction temperature (calc), T_{HJ} , °C	834	-----	842	-----	846	-----	854	-----	848	845	
Cold junction temperature (meas), T_{CJ} , °C	453	-----	481	-----	467	-----	488	-----	474	473	
Temperature difference, ΔT , °C	381	-----	361	-----	379	-----	366	-----	374	372	
Radiator temperature (meas), T_R , °C	420	-----	449	-----	416	-----	441	-----	424	430	
Voltage, V	0.1749	0.1623	0.1572	0.1736	0.1726	0.1704	0.1614	0.1442	0.1686	---	
Run 21-7; current, 2.74 A; total voltage, 1.005 V; total power, 2.76 W											
Hot junction temperature (calc), T_{HJ} , °C	835	-----	834	-----	845	-----	839	-----	843	839	
Cold junction temperature (meas), T_{CJ} , °C	463	-----	493	-----	477	-----	492	-----	486	482	
Temperature difference, ΔT , °C	372	-----	341	-----	368	-----	347	-----	357	357	
Radiator temperature (meas), T_R , °C	428	-----	458	-----	425	-----	452	-----	435	439	
Voltage, V	0.1221	0.1054	0.1027	0.1179	0.1197	0.1150	0.1065	0.0863	0.1124	---	
Run 21-8; current, 4.09 A; total voltage, 0.5012 V; total power, 2.05 W											
Hot junction temperature (calc), T_{HJ} , °C	846	-----	815	-----	853	-----	823	-----	835	834	
Cold junction temperature (meas), T_{CJ} , °C	474	-----	505	-----	488	-----	503	-----	498	494	
Temperature difference, ΔT , °C	372	-----	310	-----	365	-----	320	-----	337	340	
Radiator temperature (meas), T_R , °C	438	-----	468	-----	432	-----	461	-----	443	448	
Voltage, V	0.0690	0.0481	0.0479	0.0618	0.0665	0.0590	0.0510	0.0289	0.0565	---	

Parameter	Hot shoe number									Average
	32	52	17	45	31	48	38	46	49	
Run 21-9; current, 0; total voltage, 1.657 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	737	-----	737	-----	751	-----	745	-----	749.5	744
Cold junction temperature (meas), T_{CJ} , °C	408	-----	430	-----	422	-----	432	-----	423.5	423
Temperature difference, ΔT , °C	329	-----	307	-----	329	-----	313	-----	326	321
Radiator temperature (meas), T_R , °C	378	-----	404	-----	377	-----	398	-----	383	389
Voltage, V	0.1874	0.1833	0.1750	0.1889	0.1879	0.1856	0.1780	0.1680	0.1862	---
Run 21-10; current, 1.26 A; total voltage, 1.232 V; total power, 1.55 W										
Hot junction temperature (calc), T_{HJ} , °C	730	-----	738	-----	744	-----	742	-----	742	739
Cold junction temperature (meas), T_{CJ} , °C	416	-----	442	-----	431	-----	441.5	-----	431.5	433
Temperature difference, ΔT , °C	314	-----	296	-----	313	-----	300.5	-----	310.5	306
Radiator temperature (meas), T_R , °C	388	-----	416	-----	388	-----	410	-----	390	398
Voltage, V	0.1420	0.1329	0.1260	0.1412	0.1413	0.1369	0.1299	0.1189	0.1390	---
Run 21-11; current, 1.91 A; total voltage, 1.009 V; total power, 1.92 W										
Hot junction temperature (calc), T_{HJ} , °C	729	-----	731	-----	743	-----	738	-----	739	736
Cold junction temperature (meas), T_{CJ} , °C	420.5	-----	445	-----	435	-----	446	-----	436	437
Temperature difference, ΔT , °C	308.5	-----	286	-----	308	-----	292	-----	303	299
Radiator temperature (meas), T_R , °C	392	-----	419	-----	392	-----	413	-----	396	402
Voltage, V	0.1185	0.1079	0.1019	0.1166	0.1181	0.1124	0.1060	0.0939	0.1143	---
Run 21-12; current, 3.23 A; total voltage, 0.550 V; total power, 1.78 W										
Hot junction temperature (calc), T_{HJ} , °C	732	-----	715	-----	744	-----	725	-----	734	730
Cold junction temperature (meas), T_{CJ} , °C	430	-----	455.5	-----	444	-----	456.5	-----	448	447
Temperature difference, ΔT , °C	302	-----	259.5	-----	300	-----	268.5	-----	286	283
Radiator temperature (meas), T_R , °C	401	-----	428	-----	401	-----	422	-----	407	412
Voltage, V	0.0704	0.0559	0.0521	0.0652	0.0693	0.0619	0.0555	0.0410	0.0629	---
Run 21-13; current, 0; total voltage, 1.329 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	633	-----	633	-----	650	-----	642.5	-----	647	641
Cold junction temperature (meas), T_{CJ} , °C	370	-----	389	-----	386	-----	394.5	-----	384	385
Temperature difference, ΔT , °C	263	-----	244	-----	264	-----	248	-----	263	256
Radiator temperature (meas), T_R , °C	345	-----	371	-----	347	-----	365	-----	350	355
Voltage, V	0.1503	0.1486	0.1395	0.1514	0.1508	0.1448	0.1418	0.1359	0.1506	---
Run 21-14; current, 1.037 A; total voltage, 1.002 V; total power, 1.04 W										
Hot junction temperature (calc), T_{HJ} , °C	630	-----	640	-----	646	-----	644	-----	642	640
Cold junction temperature (meas), T_{CJ} , °C	375	-----	402.5	-----	392	-----	401	-----	389	392
Temperature difference, ΔT , °C	255	-----	237.5	-----	254	-----	243	-----	253	248
Radiator temperature (meas), T_R , °C	350	-----	379	-----	351	-----	370	-----	354	361
Voltage, V	0.1165	0.1110	0.1013	0.1141	0.1161	0.1087	0.1060	0.0993	0.1152	---
Run 21-15; current, 2.24 A; total voltage, 0.612 V; total power, 1.37 W										
Hot junction temperature (calc), T_{HJ} , °C	629	-----	625	-----	644	-----	633	-----	636	633
Cold junction temperature (meas), T_{CJ} , °C	383	-----	408	-----	400	-----	410	-----	396	399
Temperature difference, ΔT , °C	246	-----	217	-----	244	-----	223	-----	240	234
Radiator temperature (meas), T_R , °C	359	-----	381	-----	360	-----	377	-----	360	367
Voltage, V	0.0752	0.0660	0.0589	0.0706	0.0742	0.0658	0.0622	0.0543	0.0720	---
Run 21-16; current, 3.03 A; total voltage, 0.3571 V; total power, 1.08 W										
Hot junction temperature (calc), T_{HJ} , °C	635	-----	611	-----	650	-----	624	-----	637	631
Cold junction temperature (meas), T_{CJ} , °C	389	-----	413	-----	405	-----	416	-----	402.5	405
Temperature difference, ΔT , °C	246	-----	198	-----	245	-----	208	-----	234.5	226
Radiator temperature (meas), T_R , °C	366	-----	392	-----	364	-----	382	-----	367	375
Voltage, V	0.0479	0.0369	0.0311	0.0421	0.0475	0.0379	0.0343	0.0252	0.0434	---

Parameter	Hot shoe number									Average
	50	59	28	58	26	61	27	23	30	
Run 2-1; current, 4.78 A; total voltage, 0.5122 A; total power, 2.45 W										
Hot junction temperature (calc), T_{HJ} , °C	889	-----	942	-----	932	-----	912	-----	946	924
Cold junction temperature (meas), T_{CJ} , °C	527	-----	523	-----	534	-----	535	-----	513	526
Temperature difference, ΔT , °C	362	-----	419	-----	398	-----	377	-----	433	398
Voltage, V	0.0498	0.0393	0.0655	0.0657	0.0590	0.0596	0.0529	0.0377	0.0698	---
Run 2-2; current, 3.46 A; total voltage, 1.006 V; total power, 3.48 W										
Hot junction temperature (calc), T_{HJ} , °C	914	-----	928	-----	929	-----	922	-----	928	924
Cold junction temperature (meas), T_{CJ} , °C	514	-----	511	-----	519	-----	522	-----	500	513
Temperature difference, ΔT , °C	400	-----	417	-----	410	-----	400	-----	428	411
Voltage, V	0.1072	0.0944	0.1164	0.1218	0.1123	0.1174	0.1073	0.0903	0.1226	---
Run 2-3; current, 2.1 A; total voltage, 1.509 V; total power, 3.160 W										
Hot junction temperature (calc), T_{HJ} , °C	924	-----	928	-----	931	-----	930	-----	929	928
Cold junction temperature (meas), T_{CJ} , °C	500	-----	500	-----	507	-----	509	-----	491	501
Temperature difference, ΔT , °C	424	-----	428	-----	424	-----	421	-----	438	427
Voltage, V	0.1660	0.1509	0.1690	0.1788	0.1660	0.1766	0.1633	0.1440	0.1769	---
Run 2-4; current, 0; total voltage, 2.24 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	934	-----	924	-----	928	-----	932	-----	935	931
Cold junction temperature (meas), T_{CJ} , °C	486	-----	487	-----	492	-----	495	-----	476	487
Temperature difference, ΔT , °C	448	-----	437	-----	436	-----	437	-----	459	444
Voltage, V	0.2511	0.2329	0.2453	0.2617	0.2443	0.2630	0.2449	0.2220	0.2565	---
Run 2-5; current, 4.3 A; total voltage, 0.494 V; total power, 2.12 W										
Hot junction temperature (calc), T_{HJ} , °C	809	-----	845	-----	846	-----	825	-----	847	834
Cold junction temperature (meas), T_{CJ} , °C	486	-----	487	-----	493	-----	495	-----	477	488
Temperature difference, ΔT , °C	323	-----	358	-----	353	-----	330	-----	370	346
Voltage, V	0.0490	0.0399	0.0599	0.0619	0.0585	0.0584	0.0511	0.0392	0.0640	---
Run 2-6; current, 2.87 A; total voltage, 1.009 V; total power, 2.89 W										
Hot junction temperature (calc), T_{HJ} , °C	830	-----	838	-----	843	-----	838	-----	838	837
Cold junction temperature (meas), T_{CJ} , °C	473	-----	474	-----	478	-----	482	-----	464	474
Temperature difference, ΔT , °C	357	-----	364	-----	365	-----	356	-----	374	363
Voltage, V	0.1088	0.0972	0.1129	0.1203	0.1137	0.1190	0.1080	0.0942	0.1195	---
Run 2-7; current, 1.42 A; total voltage, 1.513 V; total power, 2.15 W										
Hot junction temperature (calc), T_{HJ} , °C	841	-----	841	-----	844	-----	844	-----	839	842
Cold junction temperature (meas), T_{CJ} , °C	463	-----	465	-----	466	-----	470	-----	453	463
Temperature difference, ΔT , °C	378	-----	376	-----	378	-----	374	-----	386	379
Voltage, V	0.1673	0.1537	0.1657	0.1770	0.1676	0.1785	0.1642	0.1475	0.1746	---
Run 2-8; current, 0; total voltage, 2.011 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	851	-----	843	-----	848	-----	848	-----	850	848
Cold junction temperature (meas), T_{CJ} , °C	453	-----	459	-----	458	-----	461	-----	446	455
Temperature difference, ΔT , °C	398	-----	384	-----	390	-----	387	-----	404	393
Voltage, V	0.2256	0.2095	0.2173	0.2340	0.2209	0.2370	0.2199	0.2004	0.2290	---

Parameter	Hot shoe number									Average
	50	59	28	58	26	61	27	23	30	
Run 2-9; current, 3.51 A; total voltage, 0.5272 V; total power, 1.85 W										
Hot junction temperature (calc), T_{HJ} , °C	730	-----	747	-----	755	-----	740	-----	743	743
Cold junction temperature (meas), T_{CJ} , °C	443	-----	450	-----	446	-----	457	-----	458	451
Temperature difference, ΔT , °C	287	-----	297	-----	309	-----	283	-----	285	292
Voltage, V	0.0564	0.0483	0.0603	0.0647	0.0654	0.0640	0.0549	0.0440	0.0558	---
Run 2-10; current, 2.09 A; total voltage, 1.031 V; total power, 2.15 W										
Hot junction temperature (calc), T_{HJ} , °C	745	-----	751	-----	755	-----	752	-----	755	752
Cold junction temperature (meas), T_{CJ} , °C	432	-----	441	-----	435	-----	443	-----	443	439
Temperature difference, ΔT , °C	313	-----	310	-----	320	-----	309	-----	312	313
Voltage, V	0.1139	0.1039	0.1120	0.1220	0.1187	0.1229	0.1110	0.0978	0.1135	---
Run 2-11; current, 0.702 A; total voltage, 1.489 V; total power, 1.04 W										
Hot junction temperature (calc), T_{HJ} , °C	751	-----	756	-----	756	-----	757	-----	757	755
Cold junction temperature (meas), T_{CJ} , °C	422	-----	434	-----	427	-----	432	-----	429	429
Temperature difference, ΔT , °C	329	-----	322	-----	329	-----	325	-----	328	326
Voltage, V	0.1666	0.1546	0.1597	0.1739	0.1666	0.1766	0.1621	0.1469	0.1654	---
Run 2-12; current, 0; total voltage, 1.718 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	757	-----	751	-----	758	-----	758	-----	758	756
Cold junction temperature (meas), T_{CJ} , °C	418	-----	429	-----	423	-----	428	-----	423	424
Temperature difference, ΔT , °C	339	-----	322	-----	335	-----	330	-----	335	332
Voltage, V	0.1933	0.1799	0.1834	0.1999	0.1910	0.2035	0.1880	0.1710	0.1911	---
Run 2-14; current, 3.05 A; total voltage, 0.4070 V; total power, 1.24 W										
Hot junction temperature (calc), T_{HJ} , °C	625	-----	639	-----	654	-----	634	-----	638	638
Cold junction temperature (meas), T_{CJ} , °C	399	-----	412	-----	404	-----	408	-----	406	406
Temperature difference, ΔT , °C	226	-----	227	-----	250	-----	226	-----	232	232
Voltage, V	0.0423	0.0365	0.0429	0.0495	0.0518	0.0487	0.0424	0.0359	0.0449	---
Run 2-15; current, 2.01 A; total voltage, 0.7421 V; total power, 1.49 W										
Hot junction temperature (calc), T_{HJ} , °C	633	-----	642	-----	646	-----	639	-----	641	640
Cold junction temperature (meas), T_{CJ} , °C	390	-----	403	-----	393	-----	398	-----	395	396
Temperature difference, ΔT , °C	243	-----	239	-----	253	-----	241	-----	246	244
Voltage, V	0.0807	0.0737	0.0780	0.0874	0.0874	0.0880	0.0793	0.0716	0.0825	---
Run 2-16; current, 1.17 A; total voltage, 1.005 V; total power, 1.175 W										
Hot junction temperature (calc), T_{HJ} , °C	639	-----	644	-----	645	-----	642	-----	643	643
Cold junction temperature (meas), T_{CJ} , °C	384	-----	397	-----	386	-----	391	-----	388	389
Temperature difference, ΔT , °C	255	-----	247	-----	259	-----	251	-----	255	254
Voltage, V	0.1114	0.1030	0.1053	0.1174	0.1153	0.1190	0.1087	0.0994	0.1114	---
Run 2-17; current, 0; total voltage, 1.363 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	646	-----	643	-----	647	-----	645	-----	645	645
Cold junction temperature (meas), T_{CJ} , °C	378	-----	393	-----	379	-----	385	-----	381	383
Temperature difference, ΔT , °C	268	-----	250	-----	268	-----	260	-----	264	262
Voltage, V	0.1532	0.1427	0.1430	0.1580	0.1533	0.1612	0.1485	0.1370	0.1508	---

Test Section 3

Parameter	Hot shoe number									Average
	51	54	29	60	43	64	44	62	42	
Run 5-5; current, 0; total voltage, 2.239 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	960	-----	941	-----	966	-----	939	-----	953	952
Cold junction temperature (meas), T_{CJ} , °C	530	-----	515	-----	529	-----	505	-----	490	514
Temperature difference, ΔT , °C	430	-----	426	-----	437	-----	434	-----	463	438
Voltage, V	0.2410	0.2335	0.2383	0.2546	0.2444	0.2653	0.2430	0.2409	0.2593	---
Run 5-6; current, 1.98 A; total voltage, 1.499 V; total power, 2.96 W										
Hot junction temperature (calc), T_{HJ} , °C	954	-----	944	-----	956	-----	935	-----	939	946
Cold junction temperature (meas), T_{CJ} , °C	540	-----	529	-----	539	-----	515	-----	500	525
Temperature difference, ΔT , °C	414	-----	415	-----	417	-----	420	-----	439	421
Voltage, V	0.1591	0.1480	0.1603	0.1701	0.1620	0.1801	0.1638	0.1584	0.1794	---
Run 5-7; current, 3.29 A; total voltage, 1.006 V; total power, 3.31 W										
Hot junction temperature (calc), T_{HJ} , °C	943	-----	939	-----	946	-----	929	-----	941	940
Cold junction temperature (meas), T_{CJ} , °C	547	-----	536	-----	546	-----	522	-----	508	532
Temperature difference, ΔT , °C	396	-----	403	-----	400	-----	407	-----	433	408
Voltage, V	0.1049	0.0907	0.1086	0.1138	0.1073	0.1240	0.1111	0.1033	0.1257	---
Run 5-8; current, 4.49 A; total voltage, 0.5294 V; total power, 2.37 W										
Hot junction temperature (calc), T_{HJ} , °C	922	-----	932	-----	932	-----	924	-----	953	933
Cold junction temperature (meas), T_{CJ} , °C	552	-----	543	-----	554	-----	530	-----	516	539
Temperature difference, ΔT , °C	370	-----	389	-----	378	-----	394	-----	437	394
Voltage, V	0.0530	0.0359	0.0584	0.0598	0.0551	0.0694	0.0600	0.0506	0.0737	---
Run 7-3; current, 4.22 A; total voltage, 0.4780 V; total power, 2.02 W										
Hot junction temperature (calc), T_{HJ} , °C	845	-----	852	-----	854	-----	838	-----	858	849
Cold junction temperature (meas), T_{CJ} , °C	504	-----	498	-----	510	-----	494	-----	481	497
Temperature difference, ΔT , °C	341	-----	354	-----	344	-----	344	-----	377	352
Voltage, V	0.0510	0.0335	0.0550	0.0540	0.0520	0.0613	0.0519	0.0447	0.0625	---
Run 7-4; current, 2.81 A; total voltage, 1.007 V; total power, 2.82 W										
Hot junction temperature (calc), T_{HJ} , °C	854	-----	849	-----	861	-----	844	-----	849	851
Cold junction temperature (meas), T_{CJ} , °C	490	-----	484	-----	496	-----	483	-----	470	485
Temperature difference, ΔT , °C	364	-----	365	-----	365	-----	361	-----	379	366
Voltage, V	0.1099	0.0945	0.1108	0.1142	0.1103	0.1216	0.1084	0.1035	0.1195	---
Run 7-5; current, 1.46 A; total voltage, 1.502 V; total power, 2.19 W										
Hot junction temperature (calc), T_{HJ} , °C	858	-----	851	-----	865	-----	848	-----	848	854
Cold junction temperature (meas), T_{CJ} , °C	477	-----	473	-----	484	-----	471	-----	458	473
Temperature difference, ΔT , °C	381	-----	378	-----	381	-----	377	-----	390	381
Voltage, V	0.1650	0.1516	0.1624	0.1706	0.1647	0.1778	0.1617	0.1586	0.1729	---
Run 7-6; current, 0; total voltage, 2.041 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	865	-----	850	-----	872	-----	849	-----	859	859
Cold junction temperature (meas), T_{CJ} , °C	468	-----	463	-----	475	-----	462	-----	450	464
Temperature difference, ΔT , °C	397	-----	387	-----	397	-----	387	-----	409	395
Voltage, V	0.2251	0.2135	0.2193	0.2322	0.2246	0.2395	0.2197	0.2186	0.2317	---

Parameter	Hot shoe number									Average
	51	54	29	60	43	64	44	62	42	
Run 8-4; current, 3.53 A; total voltage, 0.460 V; total power, 1.62 W										
Hot junction temperature (calc), T_{HJ} , °C	735	-----	740	-----	753	-----	730	-----	744	740
Cold junction temperature (meas), T_{CJ} , °C	452	-----	450	-----	463	-----	454	-----	436	451
Temperature difference, ΔT , °C	283	-----	290	-----	290	-----	276	-----	208	289
Voltage, V	0.0495	0.0369	0.0522	0.0530	0.0518	0.0526	0.0472	0.0462	0.0586	---
Run 8-5; current, 1.989 A; total voltage, 1.006 V; total power, 1.99 W										
Hot junction temperature (calc), T_{HJ} , °C	744	-----	739	-----	758	-----	739	-----	738	744
Cold junction temperature (meas), T_{CJ} , °C	437	-----	434	-----	451	-----	440	-----	422	437
Temperature difference, ΔT , °C	307	-----	305	-----	307	-----	299	-----	316	307
Voltage, V	0.1112	0.1001	0.1099	0.1153	0.1111	0.1113	0.1057	0.1069	0.1177	---
Run 8-6; current, 0.687 A; total voltage, 1.452 V; total power, 1.00 W										
Hot junction temperature (calc), T_{HJ} , °C	749	-----	743	-----	763	-----	746	-----	739	748
Cold junction temperature (meas), T_{CJ} , °C	428	-----	426	-----	442	-----	432	-----	413	428
Temperature difference, ΔT , °C	321	-----	317	-----	321	-----	314	-----	326	320
Voltage, V	0.1605	0.1514	0.1567	0.1663	0.1606	0.1630	0.1535	0.1567	0.1661	---
Run 8-7; current, 0; total voltage, 1.689 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	751	-----	739	-----	763	-----	740	-----	744	747
Cold junction temperature (meas), T_{CJ} , °C	423	-----	421	-----	436	-----	425	-----	408	423
Temperature difference, ΔT , °C	328	-----	318	-----	327	-----	315	-----	336	324
Voltage, V	0.1869	0.1787	0.1811	0.1931	0.1866	0.1902	0.1792	0.1829	0.1918	---
Run 8-8; current, 3.08 A; total voltage, 0.3692 V; total power, 1.13 W										
Hot junction temperature (calc), T_{HJ} , °C	640	-----	642	-----	658	-----	631	-----	643	643
Cold junction temperature (meas), T_{CJ} , °C	406	-----	405	-----	421	-----	411	-----	391	407
Temperature difference, ΔT , °C	234	-----	237	-----	237	-----	220	-----	252	236
Voltage, V	0.0409	0.0316	0.0421	0.0432	0.0419	0.0353	0.0363	0.0390	0.0477	---
Run 8-9; current, 1.94 A; total voltage, 0.758 V; total power, 1.47 W										
Hot junction temperature (calc), T_{HJ} , °C	646	-----	645	-----	664	-----	643	-----	641	648
Cold junction temperature (meas), T_{CJ} , °C	397	-----	398	-----	413	-----	403	-----	384	399
Temperature difference, ΔT , °C	249	-----	247	-----	251	-----	240	-----	257	249
Voltage, V	0.0840	0.0759	0.0823	0.0869	0.0848	0.0793	0.0780	0.0819	0.0894	---
Run 8-10; current, 0; total voltage, 1.380 V; total power, 0										
Hot junction temperature (calc), T_{HJ} , °C	651	-----	642	-----	666	-----	641	-----	645	649
Cold junction temperature (meas), T_{CJ} , °C	383	-----	385	-----	398	-----	388	-----	371	385
Temperature difference, ΔT , °C	268	-----	257	-----	268	-----	253	-----	274	264
Voltage, V	0.1530	0.1468	0.1471	0.1577	0.1536	0.1519	0.1446	0.1510	0.1567	---

APPENDIX B

RCA LIFE-TESTING OF SOLAR THERMOELECTRIC PROTOTYPE TEST SECTION

Under contract NAS3-12443, an uncoated solar panel test section, fabricated under contract NAS3-10600, was life-tested at RCA, Harrison, New Jersey, for 5500 hours at reference design conditions with fixed input power. The test section was identical to those described in the main body of this report except for the following:

- (1) The thermocouple mount studs were steel rather than beryllium.
- (2) The radiator plate was aluminum rather than beryllium.
- (3) The radiator surface was coated with aquadag rather than calcium titanate.

For this test section, the design power of 2.81 watts at 1 volt was again achieved at the design temperature difference of 361°C ; however, the required increase in hot and cold junction temperatures relative to reference design values was 40°C rather than 50°C .

The results of the life-testing are shown in figure 8 for a calculated average hot junction temperature of 830°C . During this test, the external load was periodically adjusted to maintain a load-resistance-to-internal-resistance ratio of approximately 1.2. After the first 1500 hours, the power degraded from 2.81 to 2.63 watts, or 6.6 percent, while an additional 1 percent degradation occurred between 1500 and 5500 hours.

The internal resistance R_i of the nine-thermocouple module was determined using the relation:

$$R_i = \frac{V'_{OC} - V_L}{I} \quad (B1)$$

where

V_L load voltage

V'_{OC} instantaneous open-circuit voltage

I current

The "instantaneous" open-circuit voltage is usually measured within 1 second after opening the circuit. As shown in figure 8, the internal resistance of the panel increased from 300 milliohms to about 353 milliohms after 5500 hours of testing. This increase in resistance, about 18 percent, is attributed to precipitation of phosphorus dopant in the n-type Si-Ge which is a function of both time and temperature (ref. 5)

At the conclusion of the 5500 hour life-test, the test section was disassembled and one of the nine Si-Ge thermocouples was metallographically examined. No change in appearance was observed relative to the as-fabricated thermocouples. The remaining eight thermocouples were inspected for total resistance, element resistance, and bond-contact resistance. A comparison of the room-temperature resistance for the couples as fabricated and after 5500 hours is shown in table II. Here it can be seen that the increase in couple resistance after 5500 hours is due almost entirely to increased resistance in the n-type Si-Ge.

The apparent discrepancy between the increase in resistance at operating temperature, about 18 percent, and at room temperature, about 50 percent, after 5500 hours is due to the relatively slow module cool-down rate, typically about 2 hours from reference operating temperatures to room temperature. During this time, additional precipitation of phosphorus occurs due to the decreasing solubility of phosphorus in Si-Ge with decreasing temperature, and hence, causes a substantial increase in room temperature resistance. This effect is reversible, and subsequent heating of the test section to higher temperatures would allow the precipitated phosphorus to go back into solid solution with the Si-Ge.

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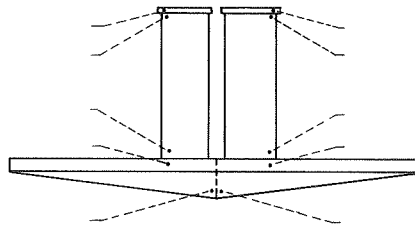
TABLE I. - JUNCTION TEMPERATURES REQUIRED TO ACHIEVE
REFERENCE DESIGN POWER AT 1 VOLT

	Reference design	Panel 1	Panel 2	Panel 3
Hot junction temperature, T_{HJ} , °C	791	^a 839	^a 837	^a 851
Cold junction temperature, T_{CJ} , °C	430	^b 482	^b 474	^b 485
Temperature difference, ΔT , °C	361	357	363	366
Power output, P_O , W	2.81	2.76	2.89	2.82
Voltage, V	1.000	1.005	1.009	1.007

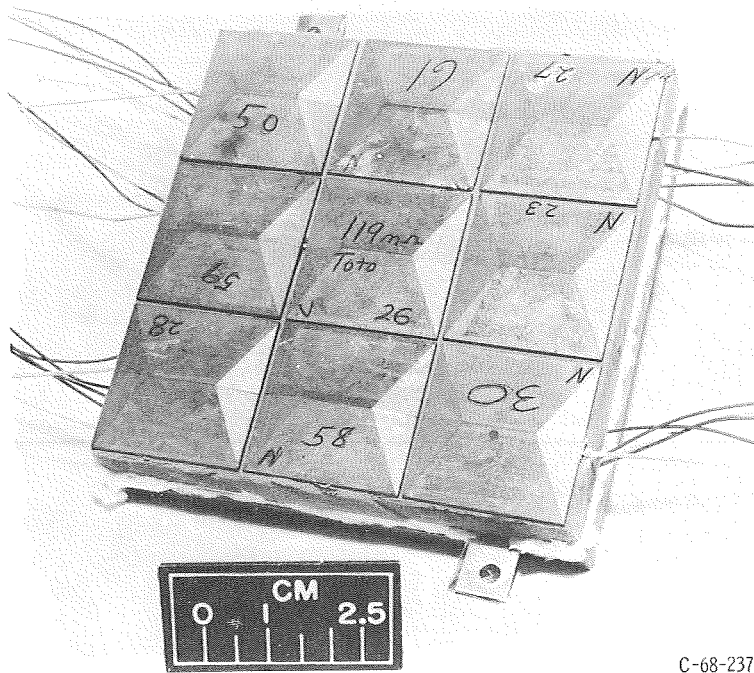
^aCalculated, average of five of nine Si-Ge thermocouples.

^bMeasured, average of five of nine Si-Ge thermocouples.

TABLE II. - TEST PANEL THERMOCOUPLE RESISTANCE DATA SHEET



Module position	Thermo-couple number	As fabricated										After 5574 hours									
		Resistance, mΩ																			
		A-B	B-C	C-D	E-F	G-H	H-J	J-K	A-K	A-D	G-K	A-B	B-C	C-D	E-F	G-H	H-J	J-K	A-K	A-D	G-K
1	25	0.37	6.00	0.30	0.16	0.40	4.89	0.33	12.6	6.67	5.62	0.33	7.13	0.92	0.32	0.35	7.40	2.35	18.40	7.38	10.10
2	37	.36	6.31	.20	.16	.51	5.30	.39	13.4	6.87	6.20	.31	6.53	.96	.23	.46	7.83	3.71	20.50	7.80	12.00
4	39	.46	6.37	.19	.15	.23	5.34	.34	13.3	7.02	5.91	.25	6.62	.94	.31	.34	7.41	3.15	19.80	7.81	10.90
5	35	.32	6.26	.35	.13	.34	4.74	.19	12.6	6.93	5.27	.29	6.19	1.05	.38	.49	7.57	1.44	17.80	7.53	9.50
6	40	.38	6.55	.15	.18	.32	5.59	.21	13.6	7.08	6.12	.34	6.64	.83	.35	.37	7.90	4.73	21.60	7.81	13.00
7	33	.24	5.96	.33	.20	.45	4.61	.15	12.1	6.53	5.21	.33	5.96	.92	.32	.38	6.61	1.96	17.50	7.21	8.95
8	41	.42	6.54	.17	.13	.22	5.46	.46	13.7	7.13	6.12	.26	6.79	.87	.28	.41	7.55	3.84	20.50	7.92	11.80
9	34	.36	6.05	.37	.11	.39	4.75	.19	12.4	6.78	5.33	.31	6.18	1.21	.44	.47	6.53	1.98	17.60	7.70	8.98



C-68-2376

Figure 1. - Silicon-germanium solar thermoelectric test panel.

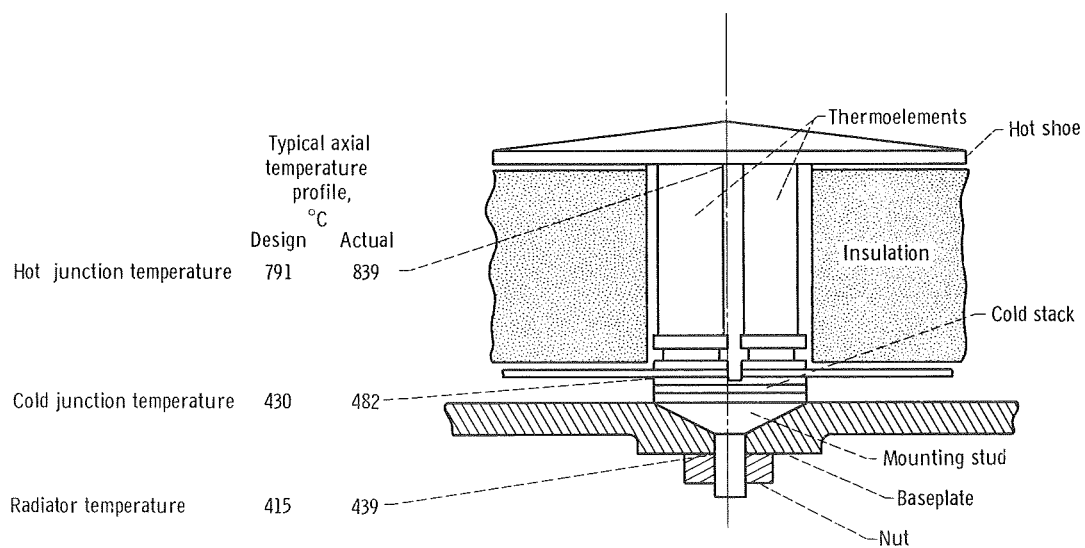


Figure 2. - Thermocouple assembly with typical axial temperature profile at reference design power.

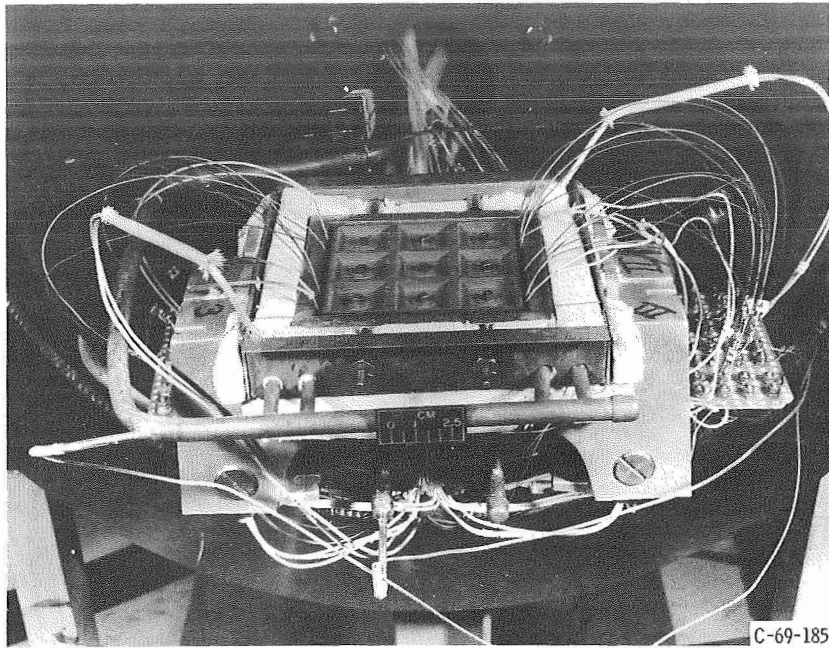


Figure 3. - Solar thermoelectric panel mounted in test fixture, showing ribbed beryllium radiator surface.

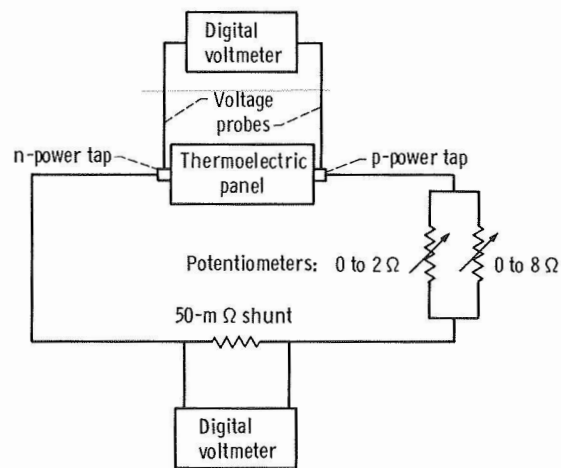


Figure 4. - Schematic of thermoelectric circuit.

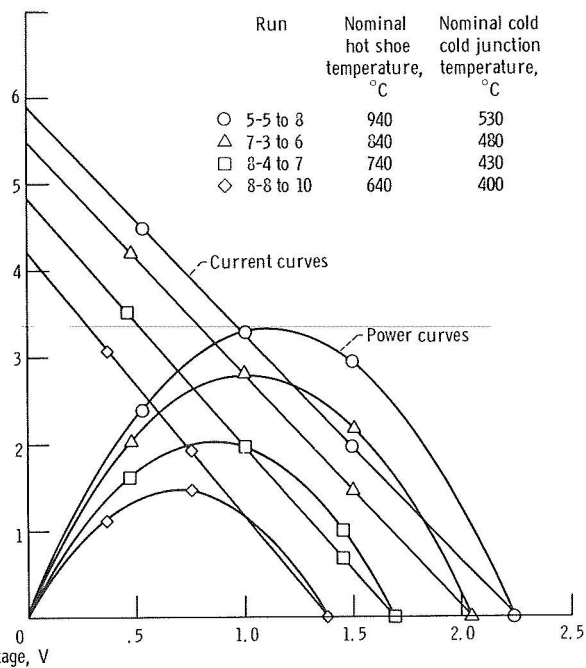
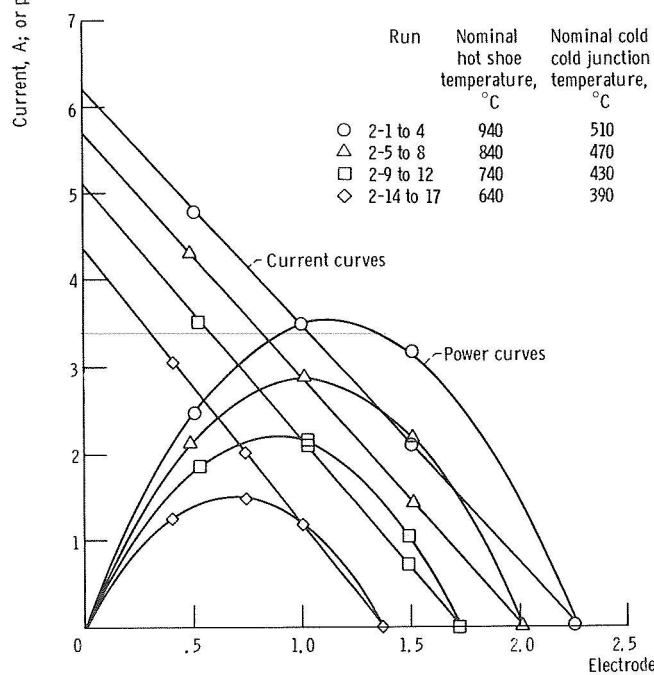
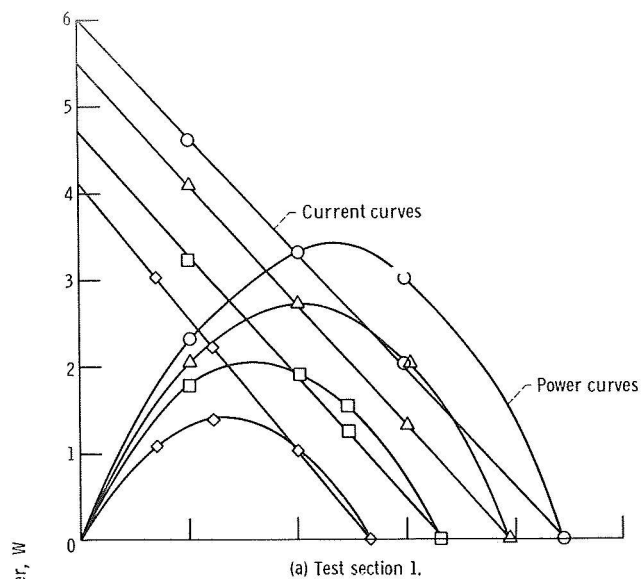


Figure 5. - Current and power as functions of electrode voltage.



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